ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

33
12 P
MFC

FINAL REPORT

PROJECT NO. E-106

AN EXPERIMENTAL STUDY OF CONCRETE MIX DESIGN BASED ON SMITH'S CONCRETE TABLES

By

RAYMOND TOOKE, JR.

and

J. T. BAIN

- o - o - o - o -

JUNE 23, 1955

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

Although many methods of concrete proportioning have been proposed, no single method has become generally accepted as superior. All of the methods in use have appeared to have both advantages and limitations and concrete laboratories have, in most cases, combined and modified methods to fit their particular needs and preferences.

The present investigation was undertaken to provide an objective preliminary evaluation of a method of design proposed by Mr. R. A. Smith, 320 Fifth Street, N. W., Atlanta, Georgia, and described in his book, Smith's Concrete Tables. This method was believed to merit investigation because of the minimum test requirements in characterizing aggregates and the elimination of calculations in arriving at the specific proportions of ingredients. Often a trial mix will be required with even the most sophisticated of proportioning methods where unfamiliar aggregates are involved. This strongly suggests that the detailed tests of sand and coarse aggregates required by many proportioning methods represent a precision of aggregate characterization that is much greater than the precision of the design method itself. Occasionally expedience may demand that a concrete mix be designed or modified in the field. The applicability of a simple but reliable method to such situations is obvious. Therefore, while Smith's fundamental concepts are by no means new, his simplified approach has appeared to justify further examination.

II. DISCUSSION OF DESIGN METHODS

The purpose of concrete mix design is to determine the optimum proportions of cement, aggregates, and water that will produce a concrete of predictable characteristics. The concrete may be required to meet certain specifications with respect to strength, slump, workability, cement economy, and other characteristics. Even the strongest advocate of a particular method of concrete design will undoubtedly acknowledge the great importance of practical experience in designing mixes. Obviously though, direct experience cannot be applied to every new situation. Therefore, design methods find practical utility. The criterion for a design method is, of course, not the beauty of the theory but rather its actual performance in practice. Other things being equal, however, a theoretical rather than a purely empirical basis is to be preferred because of potentially broader applicability.

For the present work the design method developed by Goldbeck and Grey* was selected for comparison with Smith's method. This method has been favorably received by the industry, and is, to a considerable extent, based on fundamental considerations. The concept of the volume of voids in a coarse aggregate is applied by both Goldbeck and Smith, but in a somewhat different manner by each. Smith applies the concept also to the fine aggregate while Goldbeck uses fineness modulus for characterization of sand and modifies proportions empirically to accommodate sand variations. Specific details of the methods will be found in the references that have been cited.

- - - - - -

*Goldbeck, A. T. and Grey, V. E., Bulletin No. 11, National Crushed Stone Association, Washington, D. C. (1953).

III. EXPERIMENTAL WORK

A. General Procedure

The program was designed to provide a direct comparison of the two proportioning methods using a variety of aggregates. Two different sand gradations and three types of coarse aggregates - crushed stone, gravel, and crushed slag - were chosen for the study. A maximum stone size of one inch was used. All the required properties of the aggregates were determined in the manner prescribed by each design method, and the mixes were proportioned similarly. Each of the six possible combinations of sands and coarse aggregates was tested at 28 day design strength levels of 2000, 3000, and 4000 p.s.i. and with a design slump of approximately three inches in all cases. A total of 36 mixes was required for the complete program.

B. Aggregate Properties

All of the aggregates as well as the type 1 portland cement were obtained from regular commercial sources. The gradation of the aggregates and the fineness modulus of the sands are presented in Table I. Other properties of the aggregates as required for the calculations are presented in Table II.

C. Preparation and Testing

Copies of sample calculation sheets for Goldbeck's (N.C.S.A.) method and for Smith's method of proportioning are presented as Table III and Table IV respectively. Materials calculated to provide a 0.7 cubic foot batch were charged into a motor-driven 1.0 cubic foot capacity mixer in the order (1) stone, (2) sand, (3) cement and

TABLE I. AGGREGATE GRADATION
(ASTM C-136-46)

AGGREGATE TYPE

Cumulative Percent By Weight Retained By Sieve	Fine Sand	Coarse Sand	Crushed Granite	Gravel	Crushed Slag
1"			8.9		
3/4"			50.9	18.8	31.7
1/2"			81.3	58.8	69.6
3/8"			95.5	85.0	92.2
No.4			98.2	98.8	99.0
No.8	0.1	1.9			
No.16	1.3	15.0			
No.30	53.2	72.8			
No.50	78.4	89.4			
No.100	97.2	98.6			
(Fineness Modulus)	2.30	2.77	--	--	--

TABLE II

PROPERTIES OF AGGREGATES

Property	Test Method	Aggregate Type: Fine Sand	Coarse Sand	Crushed Granite	Gravel	Crushed Slag
Bulk Sp. Gr.	A.S.T.M. C 127-42 (fine Agg.)	2.58	2.57	2.62	2.58	2.07
Bulk Sp.Gr. (Sat'd.Surface Dry Basis)	A.S.T.M. C 128-42 (Coarse Agg.)	2.59	2.58	2.64	2.60	2.28
Apparent Sp.Gr.		2.61	2.60	2.66	2.65	2.60
Absorption, %		0.4	0.4	0.6	0.9	4.8
Moisture Content, % (As used)		0.0	0.32	0.24	0.27	1.26
Unit Weight, lbs/ft^3	A.S.T.M. C 29-42	95.0	98.0	94.2	100.8	67.4
Voids In Aggregate, %	A.S.T.M. C 30-37	40.6	39.0	43.0	37.3	47.7
Voids In Aggregate, %	Smith's	36.0	34.0	45.0	38.0	53.0

Mix No. 1
Date 6/28/54

TABLE III

CONCRETE MIX CALCULATIONS
EXAMPLE OF N.C.S.A. METHOD

Design Strength (28 days) - 2000 $\#/in^2$ Coarse Agg.-Crushed Granite

Slump - 3 in. Fine Agg.-Fine Sand F.M.-2.30

Proportioning Data

Table I

$b/b_o = 0.72$

$b = b/b_o \times b_o = 0.72 \times \frac{94.2}{62.4 \times 2.62}$

Table II

Cement, Sacks/yd^3 = 4.2

.415 Water, gal/yd^3 = 38

Moisture Data

	Saturated Surface Dry (% water)	Total Moisture (% water)
Stone	0.60	0.24
Sand	0.40	0.00

Initial Calculations

Solid Volume ft^3/yd^3 of Concrete		Dry Quantities #/yd^3 of Concrete
Cement 4.2 x 0.48	= 2.02 x 196.6	= 397
Stone 0.415 x 27	= 11.20 x 62.4 x 2.62	= 1830
Water 38/7.5	= 5.06 x 62.4	= 316
Air 0.015 x 27	= .40	
Total	18.68	
Sand 27 - 18.68 =	8.32 x 62.4 x 2.57	= 1330

Final Quantities

	(1) Dry Quantities (#/yd3)	(2) Total Water (#)	(3) Sat'd S.D.Water (#)		(4) Water Correction (#)		(5) Agg. Correction (#)	(6) Final Wgts (#/yd3)	(7) Batch wgt. for 0.7 ft.^{3} (#)
Cement	397							397	10.3
Stone	1830	4.4	11.0	+	6.6	+	4.4	1834	47.5
Sand	1330	0.0	5.3	+	5.3		--	1330	34.4
Water	316			+	11.9			328	8.5
							Totals	3889	100.7

Batch Weight = $\frac{\text{Batch Vol.} \times (6)}{27}$ Total = .0259 x 3889 = 100.8#

Mix No. 2

Date: 6/28/54

TABLE IV

CONCRETE MIX CALCULATIONS
EXAMPLE OF SMITH'S METHOD

Design Strength - 2000 $\#/in^2$ — Coarse Agg.- Crushed Granite

Slump - 3 in. — Fine Agg. - Fine Sand F.M.-2.30

Proportioning Data

Voids in Sand - 36 % — Exc's. Cem. Paste - 0.0 %

Voids in Stone - 45 % — Exc's. Mortar - 60.0 %

Table Reference p. 117 — Workability - 0

Initial Calculations / Moisture Data

	Gross Volume ft^3/yd^3 of Concrete			Dry Quantities $\#/yd^3$ of Concrete		Saturated Surface Dry (% Water)	Total Moisture (% Water)
Cement	= 5.25	x	94.0	= 494	Stone	0.60	0.24
Stone	= 20.25	x	92.4	= 1870	Sand	0.40	0.00
Sand	= 14.58	x	93.0	= 1355			
Water 42.0/ 7.5 gal.	= 5.60	x	62.4	= 350			

Final Quantities

	(1) Dry Quantities ($\#/yd^3$)	(2) Total Water (#)	(3) Sat'd S.D.Water (#)	(4) Water Correction (#)	(5) Agg. Correction (#)	(6) Final Wgts ($\#/yd^3$)	(7) Batch Weight for 0.7 $ft.^3$ (#)
Cement	494					494	12.8
Stone	1870	4.5	11.2	+ 6.7	+ 4.5	1875	48.6
Sand	1355	--	5.4	+ 5.4	---	1355	35.1
Water	350			+ 12.1		362	9.4
					Totals	4086	105.9

Batch Weight = Batch $\frac{\text{Vol.} \times (6)}{27}$ Total = .0259 x 4086 = 106.0#

(4) water. The charge was mixed for three minutes and then discharged into a pan. Slump was determined in accordance with A.S.T.M. C 143-39. Three cylinders were filled according to the ASTM C-192-49 requirements for tamping and filling. After weighing, the cylinders were covered with a steel plate and allowed to set in the laboratory for twenty-four hours. Following the setting period the forms were stripped from the cylinders and the specimens were stored in a curing room at about 31°C. for twenty-eight days. The cylinders were tested at twenty-eight days by Law & Company, Atlanta, Georgia in accordance with ASTM C 39-49. All data and test results are summarized in Table V.

TABLE V

TABULATION OF CONCRETE TEST DATA

Test No.	Date Placed	Sand F.M.	Stone Type	Design 28 day St (#/in²)	Design Slump (in)	Weights per Batch (#) Cement	Stone	Sand	Water	Total	Wt. Per Cylinder (#)	Actual Slump (in)	Test 28 Day Strength (#/in²) A	B	C
1	6-28	2.30	C.G.	2000	3	10.3	47.5	34.4	8.5	100.7	27.87	1.5	1776	1663	1903
2	6-28	2.30	C.G.	2000	3	12.8	48.6	35.1	9.4	105.9	28.00	4.5	2228	2150	2150
3	6-28	2.77	C.G.	2000	3	10.3	44.2	38.0	8.4	100.9	27.40	1.0	1061	1061	1058
4	6-28	2.77	C.G.	2000	3	11.9	50.4	35.9	8.5	106.7	28.37	0.5	2455	2147	2381
5	6-29	2.30	Gravel	2000	3	10.7	47.1	34.2	8.2	100.2	27.83	1.5	1914	1964	2009
6	6-29	2.30	Gravel	2000	3	10.7	54.8	29.3	7.8	102.6	28.43	2.0	2306	2433	2441
7	6-29	2.77	Gravel	2000	3	10.7	43.6	37.8	8.1	100.2	27.77	1.0	1857	1938	1910
8	6-29	2.77	Gravel	2000	3	10.4	53.0	32.0	7.8	103.2	28.43	1.0	1875	1645	1964
9	6-30	2.30	Slag	2000	3	10.7	32.0	39.7	11.5	93.9	25.10	2.0	1139	1157	1143
10	6-30	2.30	Slag	2000	3	14.2	35.2	39.0	11.9	100.3	25.53	2.5	2999	2989	2950
11	6-30	2.77	Slag	2000	3	10.7	29.6	42.6	11.2	94.1	25.20	1.5	1284	1323	1249
12	6-30	2.77	Slag	2000	3	13.4	35.1	40.8	12.4	101.7	25.57	4.0	2133	2133	2056
13	7-1	2.30	C.G.	3000	3	11.9	47.5	33.2	8.5	101.1	28.03	1.5	2441	2589	2586
14	7-1	2.30	C.G.	3000	3	14.6	50.5	30.8	8.7	104.6	28.63	3.5	3520	3834	3572
15	7-1	2.77	C.G.	3000	3	11.9	44.1	36.6	8.4	101.0	28.20	1.5	2558	2318	2724
16	7-1	2.77	C.G.	3000	3	13.8	50.4	32.5	8.2	105.0	28.77	1.0	2855	2971	2476
17	7-2	2.30	Gravel	3000	3	12.7	47.1	32.1	8.2	100.6	28.10	1.5	2565	2423	2709
18	7-2	2.30	Gravel	3000	3	12.5	54.8	26.6	7.6	101.5	28.73	2.0	3661	3247	2936
19	7-2	2.77	Gravel	3000	3	12.7	43.6	36.1	8.1	100.5	28.27	0.5	2848	2808	2848

TABLE V (Continued)

TABULATION OF CONCRETE TEST DATA

Test No.	Date Placed	Sand F.M.	Stone Type	Design 28 day St (#/in^2)	Design Slump (in)	WEIGHTS PER BATCH (#)					Wt.Per Cylinder (#)	Actual Slump (in)	TEST 28 DAY STRENGTH (#/in^2)		
						Cement	Stone	Sand	Water	Total			A	B	C
20	7-2	2.77	Gravel	3000	3	11.9	54.8	28.1	7.2	102.0	28.83	1.0	3056	3131	2978
21	7-6	2.30	Slag	3000	3	12.7	32.0	38.1	11.5	94.3	25.30	3.5	2211	2134	2299
22	7-6	2.30	Slag	3000	3	16.6	35.2	35.3	12.7	99.8	25.87	8.0	3572	3414	3690
23	7-6	2.77	Slag	3000	3	12.7	29.6	4.10	11.2	94.5	25.30	2.0	1893	1910	1822
24	7-6	2.77	Slag	3000	3	15.8	35.1	37.2	10.6	98.7	25.97	1.0	3091	3272	3219
25	7-7	2.30	C.G.	4000	3	14.2	47.5	31.3	8.5	101.5	28.43	2.5	3516	3360	3374
26	7-7	2.30	C.G.	4000	3	15.2	50.4	29.8	8.4	103.8	28.80	1.75	4266	4577	4619
27	7-7	2.77	C.G.	4000	3	14.2	44.1	34.7	8.4	101.4	28.70	1.75	3725	3481	3622
28	7-7	2.77	C.G.	4000	3	14.4	50.4	31.6	7.9	104.3	28.93	1.0	4025	4068	3916
29	7-8	2.30	Gravel	4000	3	15.1	47.2	31.1	8.2	101.6	28.57	1.5	3806	3926	3820
30	7-8	2.30	Gravel	4000	3	13.1	54.6	25.6	7.4	100.7	28.77	1.5	3113	3124	2883
31	7-8	2.77	Gravel	4000	3	15.1	43.6	34.2	8.1	101.0	28.50	0.5	3728	3537	3481
32	7-8	2.77	Gravel	4000	3	12.4	54.8	27.2	7.0	101.4	29.00	0.5	3761	3689	3265
33	7-9	2.30	S ag	4000	3	15.1	32.0	36.2	10.3	93.6	25.80	2.0	3516	3506	3481
34	7-9	2.30	Slag	4000	3	17.9	33.8	34.9	10.8	97.4	26.00	3.0	4506	4157	4510
35	7-9	2.77	Slag	4000	3	15.1	29.6	39.1	9.7	93.5	26.07	1.0	3572	3548	3452
36	7-9	2.77	Slag	4000	3	16.8	33.8	36.9	10.2	97.7	26.10	0.75	3537	3520	3537

IV. DISCUSSION OF RESULTS

To further elucidate the comparative performance of the two design methods, the essential data of Table V have been supplemented with calculations of water-cement ratios, cement factors, volumetric accuracy of the method, and a strength-cement factor ratio. This last quantity will be taken as an indication of cement economy. These properties are presented in Table VI.

A. Slump

Neither method provided the design slump of three inches. The N.C.S.A. method was uniformly low in slump, while Smith's method averaged low but was somewhat erratic.

B. Compressive Strength

Smith's method was clearly superior in providing concrete of design strength. At the same time, the strengths of mixes in a given design strength group were more variable by Smith's method than the N.C.S.A. method.

C. Volumetric Accuracy

The maximum departure from the theoretical yield of concrete was about four percent for the N.C.S.A. method and about eleven percent for Smith's method. Variations in aggregates had a more pronounced effect on the accuracy of Smith's method.

D. Cement Economy

Smith's method will be seen to supply more strength per bag of cement in all design strength groups. It is noted as significant, however, that a given cement factor produces very nearly identical strengths by both methods. Thus, no really conclusive differences in cement economy are apparent.

TABLE VI

SUMMARY OF PROPERTIES OF MIXES

DATA FOR N. C. S. A. METHOD

Aggregates Used Sand	Aggregates Used Stone	Test No.	Slump (in.)	W/C Ratio (gal/sk)	Cement Factor (sks/yd^3)	Average Comp. Strength	Strength-Cement Factor Ratio	Actual Volume of 1 yd^3 Mix (yd^3)
MIXES DESIGNED FOR 2000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	1	1.5	9.0	4.23	1780	421	1.004
Coarse	Granite	3	1.0	9.0	4.15	1060	256	1.022
Fine	Gravel	5	1.5	8.2	4.39	1962	446	1.000
Coarse	Gravel	7	1.0	8.2	4.38	1902	435	1.003
Fine	Slag	9	2.0	9.0	4.23	1147	271	1.040
Coarse	Slag	11	1.5	9.0	4.22	1285	304	1.039
MIXES DESIGNED FOR 3000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	13	1.5	7.7	4.88	2539	520	1.002
Coarse	Granite	15	1.5	7.7	4.92	2533	515	0.997
Fine	Gravel	17	1.5	6.9	5.25	2566	489	0.997
Coarse	Gravel	19	0.5	6.9	5.28	2535	480	0.990
Fine	Slag	21	3.5	7.7	5.10	2215	435	1.035
Coarse	Slag	23	2.0	7.7	5.04	1875	372	1.040
MIXES DESIGNED FOR 4000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	25	2.5	6.5	5.88	3417	580	0.992
Coarse	Granite	27	1.7	6.5	5.94	3609	608	0.985
Fine	Gravel	29	1.5	5.8	6.28	3851	613	0.990
Coarse	Gravel	31	0.5	5.8	6.31	3582	568	0.985
Fine	Slag	33	2.0	6.4	6.16	3501	570	1.008
Coarse	Slag	35	1.0	6.4	6.23	3524	566	0.997

TABLE VI (Continued)

SUMMARY OF PROPERTIES OF MIXES

DATA FOR SMITH'S METHOD

Aggregates Used Sand	Aggregates Used Stone	Test No.	Slump (in.)	W/C Ratio (gal/sk)	Cement Factor (sks/yd^3)	Average Comp. Strength	Strength-Cement Factor Ratio	Actual Volume of 1 yd^3 Mix (yd^3)
MIXES DESIGNED FOR 2000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	2	4.5	8.0	5.01	2176	434	1.051
Coarse	Granite	4	0.5	8.0	4.68	2328	498	1.047
Fine	Gravel	6	2.0	8.0	4.39	2393	545	1.001
Coarse	Gravel	8	1.0	8.0	4.24	1828	432	1.009
Fine	Slag	10	2.5	7.0	5.35	2979	556	1.090
Coarse	Slag	12	4.0	8.0	4.98	2107	423	1.108
MIXES DESIGNED FOR 3000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	14	3.5	6.5	5.93	3642	615	1.013
Coarse	Granite	16	1.0	6.5	5.59	2767	495	1.013
Fine	Gravel	18	2.0	6.5	5.28	3281	622	0.982
Coarse	Gravel	20	1.0	6.5	4.98	3055	614	0.983
Fine	Slag	22	8.0	6.5	6.36	3559	560	1.071
Coarse	Slag	24	1.0	6.5	6.15	3194	520	1.055
MIXES DESIGNED FOR 4000 LB. COMPRESSIVE STRENGTH								
Fine	Granite	26	1.7	6.0	6.24	4487	720	0.998
Coarse	Granite	28	1.0	6.0	5.91	4003	678	1.001
Fine	Gravel	30	1.5	6.0	5.54	3040	550	0.975
Coarse	Gravel	32	0.5	6.0	5.25	3568	680	0.972
Fine	Slag	34	3.0	6.0	7.06	4391	622	1.041
Coarse	Slag	36	0.5	6.0	6.64	3531	532	1.040

V. OBSERVATIONS AND CONCLUSIONS

The limited size and scope of this investigation does not permit a development of broad generalizations. Therefore, all observations and conclusions should be regarded as tentative except for the specific systems studied.

It was pointed out in the Discussion of Results that Smith's method is less uniform than the N.C.S.A. method throughout the entire study with respect to slump, and volume uniformity (actual volume of a calculated one cubic yard mix). These observations suggest that Smith's method may have one or both of the following shortcomings:

1. The method of determining voids in aggregates may be inadequate.
2. The theory of proportioning may not be sufficiently general to accommodate the aggregate variations investigated.

The first item might be easily corrected by more careful attention to technique. The second item may require a modification of the theory. This subject is discussed in some detail in the Appendix.

Neither of the methods were entirely satisfactory with respect to the development of specified compressive strength. Smith's method was definitely superior in this property, but the strength values still exhibited excessive variation. The N.C.S.A. method averaged about 500 p.s.i. below specified strength and was also variable.

The following general conclusions are drawn:

1. Neither the N.C.S.A. method nor Smith's method of concrete design can be relied on without trial mixes for proportioning concrete using various aggregates.

2. Smith's method operates with a precision that is competitive with the N.C.S.A. method but, nevertheless, it exhibits a lack of homogeneity in performance that suggests some imperfections in the theory.

Respectfully submitted:

Raymond Tooke, Jr.
Research Engineer

J. T. Bain
Research Assistant

Approved:

Thomas W. Jackson, Chief
Mechanical Sciences Division

Approved:

Paul K. Calaway, Director
ENGINEERING EXPERIMENT STATION

VI. APPENDIX

A. Void Volume Design Theory

The concept of void volumes as a factor in concrete mix design is not new. Indeed, it was quantitated by Talbert and Richart* in 1922. Nevertheless, their method is encumbered by the requirement for multiple laboratory determinations on water, cement, and sand mixes, and these determinations must be run on every sand used. Furthermore, they only dealt with the proportioning of coarse aggregate in a summary manner. Thus their methods have not gained wide acceptance in actual practice.

Smith's method has the great virtue of simplicity. At the same time it has limitations. He does not provide for slump adjustment in his tables, but states that this may be adjusted by varying the water slightly without loss of strength. In the absence of proof, this contention must be discarded as inconsistent with Abrams. When Smith calculates the volume of wet concrete he applies a constant factor of 1.05 to the volume of dry materials regardless of the quantity of water added. This points up the fact that the column he designates as "% EXC'S SMNT. PASTE" in the tables is actually percent excess of dry volume of cement, and further that "% EXC'S. MORTAR" is actually percent excess of dry volume of sand and cement. His values do not take account of the amount of water in the paste and the mortar, and therefore they do not represent the true volumes. Thus his calculated yields must be subject to some error, and slump and workability may not be uniformly predictable.

- - - - - -

*Bull. 137 of the Engineering Experiment Station, University of Illinois

B. Modified Design Theory

Another more fundamental approach is suggested for consideration. This involves a modification and extension of Smith's method, and is believed to eliminate several fallacies in the theory.

Let one begin with a cubic foot of cement (one sack). To this one adds the theoretical amount of water required to exactly fill the voids in the cement and produce a volume of paste that equals one cubic foot. This is somewhat similar to the basic water content as defined by Talbot and Richart*. Define this cement paste as containing 0.0% excess water. Then take cement paste and exactly fill the voids of saturated surface dry sand. This mortar is defined as containing 0.0% excess cement paste. Finally, exactly fill the voids of saturated surface dry coarse aggregate with mortar. The resultant concrete is defined as containing 0.0% excess mortar. It is offered as a hypothesis that <u>any</u> concrete made with a given type of cement can be characterized with respect to physical properties by the values of these excesses and the air content so long as the constituent materials meet ASTM specifications, and the concrete is of a workable plasticity. This hypothesis is not drawn completely from "thin air". It represents an extension of Smith's theory together with inductions from the work of Fuller and Thompson, Abrams, Talbot and Richart, Goldbeck and Grey, and others.

The hypothesis stated is adequate for specifying concretes but does not provide for mix design. A second hypothesis is submitted as follows:

(1) Workability is a function of the percent excess mortar.

(2) Workability and slump are functions of the percent excess

- - - - - -

*Bulletin 137 of the Engineering Experiment Station, University of Illinois cement paste.

(3) Workability, slump, and (inversely) strength are functions of the percent excess water and the air content.

Thus the relations of the excesses of water, paste, mortar and the air content to the physical properties of the concrete are indicated qualitatively.

Application of Abram's cement-water ratio fixes the percent excess water and the strength (ignoring air content). Slump may then be adjusted as a function of excess water and excess cement paste. Slumps might be plotted as parameters against coordinates of excess water and excess cement paste and the proper value for excess cement paste selected therefrom. Finally, to determine the excess mortar it would be necessary to have several plots for fixed values of excess water (or strength). Workabilities would be plotted on each of these as parameters against coordinates of excess cement paste and excess mortar. The proper value for excess mortar would be selected therefrom. This would fix the composition of the concrete except for the air content. This factor is beyond the scope of the presently proposed method. The possibility is offered that air may be regarded as replacing portions of the volume of water and sand. Experimental work would be required to establish this point, and for the present work air entrainment will not be considered.

It will be noted that this method of design is consistent with ASTM test methods and does not require any other tests. Accordingly, it would be possible to test the hypothesis by existing laboratory data on concrete mixes if such data could be made available. This procedure would require no laboratory work except possibly to fill gaps in the data.